Shifting the learning gears: Redesigning a project-based course on soft matter through the perspective of constructionism

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This article describes the redesign of a project-based course on soft and biological materials to include computational modeling. Including the construction of computational models in the course is described as a shift from constructivism—a theory that characterizes the development of formal reasoning, to constructionism—a theory that focuses on learning while constructing artifacts. This shift ameliorated two drawbacks in the original course: the limited conceptualization of entropy resulting from an unproductive use of the disorder metaphor, and the dependence of most students on the teacher for writing theoretical explanations for their final papers. In the redesigned curriculum, computer simulations provide concrete dynamic representations that students can draw upon for developing nuanced, formal reasoning on entropy and the 2nd law of thermodynamics. In addition, core computational models act as a flexible web that can be extended and modified, and allow a significant proportion of the students to build theoretical models on their own. We conclude that while the new design reflects a shift towards constructionism, we did not adopt a fully constructionist approach, rather a blend of constructivist and constructionist approaches.

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I. INTRODUCTION

The goal for learners in project-based science courses is to study a phenomenon and build artifacts that are required for the research or represent its results. The artifacts—an experimental setup, a computational model, a written paper, or a poster—are concrete entities related to the specific phenomenon studied. Thus, the learning goal in project-based courses is qualitatively different from "traditional" courses that focus on building and refining abstract, conceptual knowledge. Constructionism is a learning theory that posits that building and improving artifacts that embody ideas of a content domain is *the* central aspect of meaningful learning [1]. Constructionism can be viewed as a divergence from traditional Piagetian constructivism, in which building and using artifacts is just one of the means to construct knowledge but not a goal in its own right. Therefore, at first glance, project-based courses seem to be rooted in a constructionist approach, rather than a constructivist one. However, students in project-based courses need an intellectual basis—an introduction to fundamental ideas of the field—in order to build their artifacts [2–4]. Which theory should guide designers of such project-based courses that include a substantial component dedicated to building a conceptual basis for the projects?

In this paper, we describe our experience of redesigning a curriculum of such a project-based course, and ask whether it reflects a paradigm shift from constructivism to constructionism. The course focuses on the physics of soft and biological matter and is offered to highly capable high school students at a university-based science center. Student projects entail experimental investigations of material properties (e.g., the elasticity of a rubber band at different temperatures), and experimental findings are summarized in final papers alongside a rigorous, theory-based discussion. In the original course, the theoretical discussions were based on analytical, thermal-physics models utilizing the concepts of entropy and free energy [5]. The new course includes constructing and using computational Monte Carlo and Molecular Dynamics models to explain experimental results [6]. Building simulations enables students to investigate a dynamic, visual representation of the models and more importantly, allows learners to discuss phenomena for which analytical methods are beyond their level of expertise.

While both courses introduce thermal physics concepts such as entropy, the inclusion of computational models in

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the redesigned course created a new balance: less mathematical, formal models and more visual, concrete representations rooted in the simulations. This, in turn, reflects a shift in instruction: from supporting mainly mathematical derivations of theoretical relationships and concepts, to supporting the construction of computational models, and their output.

II. FRAMEWORK OF THE STUDY

A. Context of the courses

Soft matter is a contemporary, interdisciplinary field of science in which thermal physics models are applied to chemical and biological phenomena [4]. Presenting thermal physics principles in the context of soft matter, rather than the traditional context of ideal gases and harmonic oscillators, can promote a more relevant and less detached image of this topic, especially among nonphysics majors [4]. The original soft matter course was a two-year long program for 11th and 12th graders that took place after school at a university science center [4]. Students met once in two weeks in the afternoon for 3 h. The meetings dedicated to projects comprised one-quarter of the entire curriculum—approximately fifteen meetings. The students presented their projects in final papers and in oral presentations and were graded 40% of the matriculation grade in either chemistry or physics. Because of changes in the matriculation system in Israel, and competition with similar programs, we decided to upgrade the course to a full credit, standalone matriculation course (like an Advanced Placement course).

The decision to include computational modeling emerged from our research on students' perceptions of modeling in the original course [5] and a realization that computation has become an essential component of studying complex systems in general and material systems—in particular. Several pioneering science curricula include computational modeling as a learning goal [3], and due to the pervasive use of digital devices in and out of school—this trend is likely to become more prevalent in the future.

The redesigned course includes a substantial component of computational modeling, and thus requires more time. The course meets more frequently—once a week (instead of once in two weeks) at the same university science center. In addition, the program is three-years long (10th to 12th grade), not two-years long, and thus spans 2.5 the time of the original course. The 11th and 12th grade curriculum included the same topics as in the original curriculum with the addition of constructing random walk and Metropolis models [7]. The 10th grade curriculum encompasses the analysis of Brownian motion and diffusion bridging between deterministic Newtonian models and stochastic, random walk models. This part of the course is entirely new and not a redesign. Each year encompassed a project comprising approximately one-quarter of the meetings.

B. Method of redesigning the course

The redesign of the soft matter course utilized the model of educational reconstruction (MER) [8]. This model conceptualizes studies of curricular design as processes comprising three interconnected components: (a) Content analysis, (b) instructional design, and (c) empirical investigation of learning. The empirical research addresses the feasibility of the learning goals, as reflected by the learnability of the content, and the effectiveness of the instructional activities. In our case, the teachers of the course were members of the research team and were involved in all three components of the MER. Because of the unique content and small sample of students in the original and redesigned courses, the empirical research was mostly qualitative focusing on representative case study students. Important events in the students' learning were documented by the researchers, followed by clinical interviews conducted after the conclusion of the learning unit. To corroborate our findings, we triangulated the case-study data with questionnaire data that summarized the perceptions and knowledge of the entire group. Student responses to the questionnaires or interviews were analyzed based on their alignment with *a priori*, top-down categories from the literature, and new bottom-up categories that were identified by the research team.

III. THEORETICAL FOUNDATIONS: FROM CONSTRUCTIVISM TO CONSTRUCTIONISM

In the following, we focus on the theoretical distinction between constructivism and constructionism as applied to two components that are relevant to the design of our project-based course: (a) epistemology and conceptual understanding and (b) guidance and scaffolding. The first component addresses the theoretical conceptualization of how learners acquire understanding of fundamental, core ideas in the field. The second addresses the instructional support that allows learners to progress in complex research projects—a task that most introductory level learners cannot perform independently. Following Lazonder and Harmsen [9] we define guidance as "any form of assistance offered before and/or during the inquiry learning process that aims to simplify, provide a view on, elicit or supplant" the task.

A. Epistemology and conceptual understanding

The constructivist paradigm conceptualizes learning as a process of developing a better understanding of the world by constructing new knowledge on the basis of prior knowledge [10]. In constructivism, the learners *construct* their knowledge, and the building blocks are pieces of their prior knowledge and new acquired knowledge. According to this view, young children come into the classroom with a set of intuitive, concrete ideas about the world, and only later on they develop reasoning that involves abstract and sophisticated ideas. Piaget's constructivist theory of learning views the naïve, or intuitive thinking that young learners use as concrete and egocentric, and the coherent, rule-based reasoning that experienced learners develop as formal thought [11].

Constructionism emerged from Seymour Papert's pioneering research on learning with his LOGO programming language [1]. It focuses on learners' construction of knowledge and reasoning through building artifacts, and is thus particularly relevant in learning programming and in makerspaces [12]. It can be viewed as an extension of constructivism, but the focus on the interaction between learners and the objects they create leads to a divergence in the epistemology of each approach.

Constructivism is a developmental, descriptive theory of learning not a prescription for designing educational interventions [13]. However, it is also the basis of several instructional approaches or "frameworks for action" that derive ideas from it. Under the umbrella of constructivism we find *concreteness fading*—a framework for teaching learners at the early stages of developing formal or operational thinking, that progresses from experiencing concrete entities to formulating abstract ones [14]. Other constructivist-inspired approaches, such as resource refinement [15] or knowledge integration [16] assume that learners come to the classroom with naïve conceptions (or preconceptions), and suggest how teachers can relate to these ideas, refine their students' thinking, and lead them toward normative scientific reasoning. To that end, Hestenes' modeling instruction epitomizes a constructivist approach in physics [17]. It is designed to address learners' "physical intuitions"—their unarticulated beliefs that are "only weakly interrelated and frequently inconsistent" [17]—with the highly consistent beliefs of the physicist.

Let us use the concept of entropy to illustrate the constructivist' approach. Learners naturally develop the intuitive idea that a mixture does not demix (separate) spontaneously and that systems are more likely to become naturally disordered than ordered [18,19]. This idea is rooted in concrete experiences with natural systems, and can serve as a basis for constructing a central scientific principle: the 2nd law of thermodynamics. Thus, constructivism views the development of the formal, scientific concept of entropy and the 2nd law of thermodynamics as a process of refining, quantifying, and reconceptualizing the intuitive or concrete idea that things are likely to become more disordered [20].

Epistemological beliefs are important factors that shape learning according to the constructivist paradigm. Learners come to the classroom with a collection of personal epistemological beliefs on how to learn, and on what constitutes understanding [21]. These beliefs develop with age and level of education [22] and influence the acquisition of conceptual knowledge. Learners' personal epistemologies or their *epistemological framings* of a learning situation are therefore key for developing coherent scientific reasoning [23]. Formal reasoning is based on epistemologies that reflect principled logic: to seek coherence and to base the acquisition of new knowledge on few, central ideas that can be used as *footholds* for climbing the edifice of scientific reasoning [23]. Thus, the constructivist approach to learning assigns a higher status to some learner epistemologies, such as "seeking coherence between ideas," regardless of the learning context. For example, if learners develop an epistemological framing of the 2nd law of thermodynamics as a foothold idea, they will more likely investigate *how* the law applies to situations which seem counterintuitive because the entropy of the system decreases (e.g., in molecular self-assembly). Moreover, expertlike epistemological beliefs assign a higher status to abstract, formal ideas (or schemas), since these reflect a more developed status of thinking than reasoning that is connected to concrete objects or situations [24].

Viewing construction as an intrinsic property of learning in constructionism, reshapes the role of epistemology, specifically the interplay between concrete and abstract reasoning [24]. Turkle and Papert [25] lay the foundations for what they call "epistemological pluralism." They demonstrate their approach using examples from the world of programmers. They claim that although programming is a practice with strict rules, for beginners it allows a "softer" approach of building without planning, through trial and error. One of the reasons for this pluralism is that there are often many ways to write programs with the appropriate algorithm that achieve the desired result. They borrow the term "Bricolage" from anthropologist Claude Lévi-Strauss to describe this type of programming style:

> *"While hierarchy and abstraction are valued by the structured programmers'… bricoleur programmers, like Levi-Strauss's bricoleur scientists, prefer negotiation and rearrangement of their materials. The bricoleur resembles the painter who stands back between brushstrokes, looks at the canvas, and only after this contemplation, decides what to do next."* [25] (p. 7)

They claim that this "softer" approach to programming allows students that are deterred by the structured, strict style of the practice to engage in programming as bricoleurs. Specifically, they found that this style of programming is more common with girls. A Piagetian constructivist would views the bricoleur's unsystematic approach as an intermediate stage in becoming an expert programmer [26]. However, Turkle and Papert [25] have identified this style also with expert programmers, and endorse this approach as one that is more connected to the concrete computer program that is constructed than to the expert approach of how to build it. They criticize the higher status assumed for the structured, formal approaches to programming, and claim that it should not be considered the highest point of the development of programmers.

> *"Traditional epistemology gives a privileged position to knowledge that is abstract, impersonal, and detached from the knower, and treats other forms of knowledge as inferior. But feminist scholars have argued that many women [and/or scientists] prefer working with more personal, less detached knowledge and do so very successfully. If this is true, they should prefer the more concrete forms of knowledge favored by constructionism…"* [25], (p. 10).

In other words, the constructionist educator views meaningful learning as fundamentally related to the concrete artifacts that students manipulate, even when the concepts involved are abstract. Similarly, diSessa [27] argues that detached mathematical problem solving in physics reflects a formal approach that is not likely to help student construct their knowledge, whereas computer simulations can be considered "semiformal," since they represent problems in a manner that resonates with the phenomenon and has therefore a better chance to build conceptual knowledge than the formal approach [27].

To conclude, a shift from constructivism to constructionism places more value on students' connectedness to the mechanism and modeling of specific phenomena than on the development of a formal, structured approach to the field.

B. Guidance and scaffolding

High school students are novices when it comes to doing research projects [28] and thus need guidance. Vygotsky defined activities that learners can complete *only* under the guidance of an experienced mentor as the learners' zone of proximal development (Ref. [29], p. 86). The zone of proximal development can be conceptualized as an intermediate stage in the development of newcomers in a certain field of practice. Collins, Brown, and Newman [30] have borrowed from Vygotsky the interactive description of learning and introduced the term "cognitive apprenticeship" to describe the process of instructing students in complex tasks in mathematics, reading, and science. According to the cognitive apprenticeship approach, the teacher-expert guides the novice into the practice of complex academic tasks, by first modeling the practice, then providing scaffolds for the apprentice to perform a simplified version of the task. Another feature of scaffolding—designing them so that they can be gradually removed (fade) is considered essential by some researchers but not by all (e.g., Ref. [31]). The critical feature of scaffolding is to provide support for learners to be able to perform a task that would otherwise be beyond their capabilities [31]. This approach is sometimes referred to as socioconstructivism, since it conceptualizes the learning process as a social interaction between the mentor and mentee.

Scaffolding supports students in doing the task, but also in explaining the practices involved in solving it—thereby making disciplinary norms explicit [30,32]. Scaffolding entails mainly directive, structuring functions such as reducing the degrees of freedom of the task or marking its critical features [33]. However, when learning complex topics, structuring is accompanied by problematizing scaffolds that do the opposite: instead of streamlining and guiding they raise conflict and force students to ponder about their decisions and reasoning [34]. All in all the role of scaffolds is to aid learners to achieve a target performance that would be outside their reach without the scaffold.

Constructionism is a learning theory that emphasizes student-directed discovery, mainly within a computational medium. In constructionism, the learner's main interactions are with the computational medium not with a human mentor. The notions of scaffolding are therefore absent from Papert's writings. However, the learning environments themselves, such as the LOGO programming language have features that direct learners. For example, Papert writes that "The (LOGO) turtle defines a self-contained world in which certain questions are relevant, and others are not" ([25], p. 117). LOGO is a "Microworld"—a computer language that resembles a programming environment of experts in its functional form, but is designed with the need of learners in mind [31]. Papert advocated the idea that letting children play and experience a Microworld such as LOGO will enable developing mathematic and programming capabilities in a manner that resembles the spontaneous acquisition of language [25]. Similarly, diSessa argues that productive microworlds should be designed so as to represent the conceptual landscape of the topic in a familiar form and self-evident "controllability" [27].

However, the conceptual development of learners in open discovery is limited. Controlled studies with LOGO showed that without guidance most children obtain only basic programming abilities. One study showed that 5th graders who spent a significant amount of time doing unstructured projects in LOGO developed on average basic understanding of LOGO commands, but not much more than that. Conversely, an equivalent group of students who learned LOGO in a structured, guided approach using tutorials, developed programming knowledge beyond the LOGO syntax [35]. The accumulating evidence for the need of guidance, especially among lower performing students, led some proponents of the constructionist approach to reconsider the usefulness of open discovery and examine scaffolding for constructing computational artifacts.

What might be the role of scaffolding in constructionism? While constructivist framework envisions a one-way role for the scaffolds to direct and support the learners towards a target performance [31], the constructionist bricolage approach provides the learners agency in directing their own progress. Thus, scaffolding is a constructivist metaphor since it envisions support as an external rigid and directive agency, rather than a flexible and integral part of the learning environment. Instead, Noss and Hoyles [36] suggest the concept of "webbing" as a more appropriate metaphor for support according to the constructionist paradigm:

> *"The idea of webbing is meant to convey the presence of a structure that learners can draw upon and reconstruct for support—in ways that they choose as appropriate for their struggle to construct meaning…"* ([36], p. 110)

Thus, webbing differs from scaffolding since it entails procedures that learners can extend, adjust, and rearrange by themselves like a spider web. The most common example for webbing is giving students a readymade program that they can modify to discover its underlying mathematical, scientific, or computational principles. Noss and Hoyles [36] provide an example of webbing using a LOGO procedure that produces a drawing of a parallelogram that students can modify. They show how students run and adjust the program and eventually deduce the underlying geometric definition of a parallelogram. Webbing differs from scaffolds such as a catalogue of procedures, or a "help" menu, [37] that are often included in programming environments or microworlds in that it provides a "seed" for a program or a basic structure that learners can restructure.

In an educational setting with one teacher mentor and many student mentees, one-to-one mentorship would be cumbersome, and therefore supports should be preplanned for the entire group. The concepts of scaffolding and webbing usually refer to the supports that were purposefully designed and embedded in the learning materials for a group of students [38]. In addition, classroom implementations entail adaptive and personalized support by the teacher that supplement the static, material scaffolds or the preplanned webbing. Teacher support that extends and problematizes the static, preplanned scaffolds has a significant role in learners' progress [38].

To conclude, social constructivism is based on Vygotsky's idea of the zone of proximal development (ZPD) that describes a "learning territory" in which students are capable to perform tasks with the guidance of an expert. Guidance in the ZPD is based on the concept of scaffolding, adopted from descriptions of professional apprenticeships. Constructionism emphasizes free and open discovery learning, and thus seems incompatible with the directive scaffolding concept. To that end, the concept of *webbing* can be thought of as an intermediate—a dynamic and flexible form of guidance that may be adjusted by the learners.

IV. FROM CONCRETE TO FORMAL AND BACK: DESIGNING A CURRICULAR UNIT ON ENTROPY

In this section, we reflect on the redesign of the new course as a shift in learning theory that yielded different forms of productive student reasoning. Since reviewing the design of the entire curriculum of the new and old course is beyond the scope of a single paper, and since a direct comparison between the new course and the old course is impossible (due to differences in scope, duration, and student population) we focus in this section on one concept that was introduced in both courses: entropy. The section starts with the introduction of the concept of entropy in the original course that was based on the constructivist approach. Then, we describe the introduction of entropy in the redesigned, computational soft matter course. Finally, we illustrate student reasoning related to entropy in the old course and demonstrate how constructionism shaped student reasoning in the new one.

A. Introducing entropy in the original soft matter course

The original design of the soft matter course took a spiral approach. It started with a relatively brief, qualitative analysis of phenomena, and then revisited these ideas in a second spiral, using a more formal, mathematical approach. In the first part of the spiral we used the term "disorder" as a metaphor for the "number of possible arrangements" of the system. Later, we replaced this term with the mathematical counting of the number of states and the Boltzmann definition of entropy [4]. The use of the disorder metaphor is controversial: some authors argued vehemently against it since it reflects a flawed and misleading understanding of entropy [39,40]. The critics claim that "disorder" promotes a conceptualization of entropy as a single configuration of the system rather than a collection of many configurations [41], whereas other metaphors such as "a measure of energy spreading" or "the degree of ignorance" do not [41,42]. Others argued that the disorder metaphor can be a productive resource for developing a conceptual understanding of entropy, if students are given opportunities to refine their understanding of the term [43,44]. We followed the latter approach since we believe that disorder is a more intuitive metaphor than "energy spreading" or "the degree of ignorance," and that novices need a concrete basis to conceptually construct the subtle idea of entropy.

After the qualitative introduction in which entropy was presented as a measure of disorder, we dedicated three lessons to introducing the formal definition of entropy. We expected students to refine the qualitative, intuitive idea about the tendency to increase disorder, and develop a formal conceptual understanding of the 2nd law of thermodynamics. We justified the derivation of the formal, mathematical definition of entropy, on the necessity to

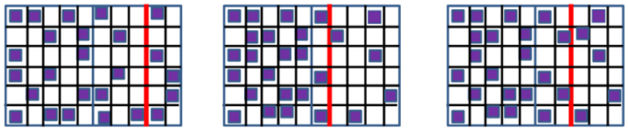


FIG. 1. The model used as a basis the quantitative definition of entropy and the 2nd law of thermodynamics in both courses. Three configurations of a system of 25 particles in a lattice with 60 sites, with a separating, nonpenetrable membrane. Five particles are located at the right side of the membrane and 20 are at the left.

"quantify" the amount of disorder in a system. We then used the lattice gas as a concrete representation for calculating the disorganization or disorder of a system. For example, the number of ways to distribute N objects in a "disorganized" lattice with M cells. We asked students to draw all the possible configurations of a small system (e.g., 3 objects in 5 cells) and developed the equation for the number of microstates (designated by the multiplicity Ω) of the system of N particles in M lattice sites. The lattice model and its visualizations shown in Fig. 1 were the basis for the formal definition of entropy. The spatial entropy analysis of two lattice-gas systems was used to show that a state that maximizes the combined entropy of the two systems is the state of equal density as shown in Fig. 1. Then, by analogy, we showed that entropy not only quantifies spatial configurations of the system, but also the number of possible organizations of energy "quanta" in the system (e.g., Refs. [45,46]). From this point on, ten lessons into the course, we used only the term entropy, alongside its quantitative expression and the lattice model and no longer used the term disorder.

B. Introducing entropy using a novel, constructionist-based approach

The new course uses simulations as central tools for analyzing physical changes in matter, and thus provides a different context for introducing the concept of entropy. Simulations allow us to depict the dynamics of systems and change the entire basis of reasoning about equilibrium states in matter. Beginning with dynamics is very novel and can only be done at the introductory level using simulations. As in the original course, we start with introducing physical processes in materials such as the flow and retraction of Silly Putty. Afterwards, students enter an in-depth study of the dynamics of diffusion and Brownian motion.

First, students build a model of an elastic-sphere gas that is based on familiar principles from Newtonian mechanics such as Newton's 2nd law and Hooke's law [6]. They use these principles to simulate springlike collisions between particles—the interactions at the origin of the diffusion phenomenon. Then, they add larger objects to the molecular dynamics model of the particle fluid—these objects represent colloidal particles. Analyzing the development of colloid particles' trajectories in different timescales reveals that the same motion can be simulated using a random force, as suggested by Langevin [47]. The so-called Langevin dynamics model justifies the shift from the Newtonian, molecular dynamics model of particles' motion, to a random walk model of colloidal particles in a solvent. The diffusion or random walk unit was designed according to a constructionist approach in which students build artifacts (computer simulations) and explore them. This unit spanned 20 lessons—much longer than the introductory unit of six lessons in the original course. The difference in duration reflects the significant proportion of modeling and programming assignments [48].

In isothermal diffusion of an ideal gas with N particles, the entropy increases as the volume occupied by the gas increases. When a gas that was initially constrained in part of the container spreads and fills the entire container, the system reaches uniform density and the entropy reaches its maximum value. In order to realize this idea, students explore the process of diffusion using a simulation of a gas of random walkers and build monitors of the local density of the simulated gas. Then, they investigate the simulation of a diffusing gas (or mixture of gases) with an initial nonuniform density, and observe how the system reaches a uniform density throughout the container. Then, in a series of three lessons the diffusion process is reconceptualized from a probabilistic standpoint: the initial, nonuniform state of a gas that fills only part of the container is shown to be less probable than the final equilibrium state [49]. The equal probability postulate that each microstate of the system is equally probable is presented with the aid of a simulation that places particles randomly in an array. Students explore the code and output of the program, and realize that while each sampled array is equally probable, the probability of a group of samples that share a similar feature—a macrostate—is not the same. For example, students build a program that places 10 "particles" randomly into an array or list of 50 "sites" and counts the fraction of samples in which all of the particles are concentrated in 25 of the 50 sites. After studying this phenomenon using the simulation, the probability of a macrostate of nonuniform distribution is calculated mathematically using the lattice-gas representation. In this task (that was used also in the original course) students calculate the number of possible configurations of each system in Fig. 1, and find that the most probable macrostate occurs when the densities at the left and right of the membrane are equal.

Since the probabilistic analysis of diffusion lends itself to ideas of estimation and prediction, we introduced entropy as a measure of the *uncertainty* of a macroscopic configuration rather than its *disorder.* Note that the concept of *uncertainty* itself is somewhat abstract and played out as a bridging metaphor rather than a concrete foundation for the idea of entropy. The concrete entity underlying the entropy concept was the simulation that represented the diffusion process.

The lessons that introduce the formal definition of entropy as the logarithm of the number of spatial configurations and then a measure of energy quanta distribution were similar to the sequence of lessons in the original course. Simulations were not used in this part of the course. To summarize, the introduction of the concept of entropy in the new course differs from the original course in two main aspects: 1. It is founded on the analysis of the dynamic diffusion process and not on the static disorder metaphor. 2. The conceptual foundation is the construction and explorations of simulations of diffusion rather than a conceptual discussion of the model.

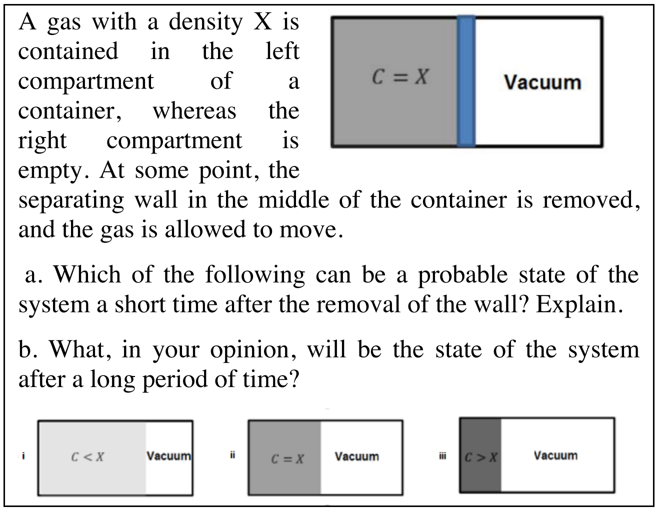
As mentioned in the introduction, the constructionist approach endorses "epistemological pluralism" that allows the learners to program and to reason as a bricoleur by moving back and forth between formal and concrete methods and ideas. In the following, we show how this approach yields productive reasoning. We also show that not all of the students become bricoleurs, and some seem to prefer the more formal and rule-based approach.

C. Concrete and formal resources for reasoning

In the original course designed according the constructivist approach, we tried to relate to students' prior ideas about disorder and to build from these ideas, the formal concept of entropy. However, for some of the students relating to disorder ideas did not yield the expected result, and students developed flawed reasoning about the concept of entropy and the 2nd law of thermodynamics. For example, in a questionnaire that we administered after the formal presentation of entropy, we asked whether processes in which the entropy of the system decreases contradict the 2nd law of thermodynamics. Approximately 30% of the students responded incorrectly—that these processes contradict the 2nd law of thermodynamics. For example, Danny wrote: "*Yes, because the 2nd law of thermodynamics requires an increase in the disorder of the system, but in a system in which the entropy decreases, the disorder decreases as well, contradicting the 2nd law*". We concluded that the disorder metaphor with its concrete connotation of disorganization of material objects hindered the conceptualization of entropy as a measure of the number of spatial configurations and spreading of energy [50].

The role of the concrete in conceptualizing processes is rather different in the novel computational soft matter course. To illustrate learning in the course, we use two interview protocols with students. Both students finished the introductory unit on diffusion and Brownian motion, and the unit comprising the formal presentation of entropy. The question in Fig. 2 was presented in the interview.

A legitimate reasoning pattern leads to the conclusion that option (iii) is the only probable state of the system. For example, student S6 responded to this question using probabilistic reasoning and without mentioning entropy.



A gas with a density X is contained in the left compartment of a container, whereas the right compartment is empty. At some point, the separating wall in the middle of the container is removed, and the gas is allowed to move.

a. Which of the following can be a probable state of the system a short time after the removal of the wall? Explain.

b. What, in your opinion, will be the state of the system after a long period of time?

FIG. 2. An interview question on gas expansion that promotes several productive reasoning resources related to entropy, random motion, and probability.

> *(S6) Because the motion (of the gas) is random it is impossible to decide whether the gas will spread and take up more volume or would remain with the same volume or even retract. But, you can say that state (i) in which the gas spreads and occupies a larger volume is more likely because when the gas has a higher density it has a more limited number of states. It goes to the most probable state, as if it occupies a … as if it becomes evenly distributed among all vacancies because this is the most probable state. Then, when more places are available, the most probable state will be to disperse evenly among all available places. After a long time, it will fill the entire volume of the container… Particles want to occupy, ummm, they move randomly as if there are more arrangement options, and they scatter all over the system (container) … which means that the macrostate with the most options for arrangement—with the most microstates—is the most probable one.*

This student integrates several ideas: that particles perform random walks ("Particles want to occupy, ummm, they move randomly"), that all macrostates are possible ("it is impossible to decide whether the gas will spread and take up more volume or would remain with the same volume or even retract") and that one of the three macrosates is more probable than the others. This response shows that the student moves back and forth between the concrete, microscopic perspective (particles perform random walks) and the more abstract, macroscopic one ("as if it becomes evenly distributed") to reach the proper response.

A second student took an entirely different approach to answer this question—an approach that seems at first more aligned with the answer of an expert since it uses the concept of entropy.

> *S8: First of all, according to what we learned in class, you have to look at this system and that system separately (the student points to the two sides of the partition). In total, according to the second law, the entropy of… if I look at it from outside—the overall entropy should increase, should be at maximum… Let's say… I would say if you asked me in a test, I would say this (option i) because entropy must increase—M (the amount of available lattice sites) increases—I have more options here. But in terms of the 2nd law, entropy cannot decrease but it can also remain the same, so basically I say that the probability of this (option ii) is almost zero but it can also be possible … but with low probability. Very, very, very, very low probability.*

This student uses a formal approach, he treats the container as a lattice with M sites and applies the concept of entropy and number of states ("M increases, I have more options here") to reason about the process. He also uses the 2nd law of thermodynamics to predict that the entropy should increase or stay the same ("but in terms of the 2nd law, entropy cannot decrease but it can also remain the same"). More concrete ideas related to random motion that are rooted in the initial unit of the course were not considered as useful reasoning resources by this student.

The limitation of this rather formal approach was revealed in a follow-up question in the interview. The interviewer showed two snapshots of configurations of a system of colloids in a solvent (Fig. 3) and asked whether both snapshots are possible, and if they are possible which one of these patterns is more probable? The left one? The right one? Are both equally probable?

S8 interprets these two pictures as representing macrostates with many possible configurations:

> *S8: Specifically, I would say the left (picture) because … the higher probability is the one where the balls actually take up more space, because you have many more options (possible configurations) when it occupies more space. You have a lot more options than when they are closer to each other.*

FIG. 3. Snapshots of a colloid system. Since snapshots are microstates of the system, and do not represent an ensemble, the two representations are equally probable.

S8 views the more spread state of the system, as more probable, and does not realize that each snapshot represents a microstate. His response echoes Styer's observation that students' tend to confuse single configurations that seem disordered, with the concept of a macrostate that represents many configurations [40]. In addition, this student does not reason about the system as a dynamic microscopic Brownian motion, rather, he uses a macroscopic generalization: more spread means more probable. Conversely, S6 continues to view the system as dynamic, and this view helps him realize a more proper conclusion:

> *S6: They are both possible…because of the random motion, every configuration is possible except when two particles overlap.*
> *Interviewer: OK and which one (snapshot) is more probable?*
> *S6: This one (points to the left one)*
> *Interviewer: Why is this one more probable?*
> *S6: Because actually… (long pause)…if both of these are microstates… they should both have the same probability…(short pause). Because each particle has the same probability of getting to a certain place in the system, so if they start from a certain point, colloid 1 has the same probability to get here and here (points to the location of colloid 1 in each picture)… I can do this for all of the colloids so that both are the same (have the same probability).*

This excerpt shows how the dynamic view helps S6 to doubt and refute his initial intuitive response—that the left picture is more probable. S6 applies the idea that after a long period of time each colloid can be anywhere in the system and thus no single configuration is more probable.

These examples demonstrate how the dynamic view, rooted in the engagement with the simulations leverages a rich set of reasoning resources for S6. It also shows that for some students such as S8, the formal introduction of entropy and the 2nd law of thermodynamics, overshadowed the concrete, dynamic reasoning about the system. We suggest that S8 leaned towards the formal, abstract approach because his epistemology is authority oriented, and the teacher, as the scientific authority was perceived as leaning towards abstract, formal presentation of entropy. This is illustrated in S8's words at the beginning of the interview excerpt: "*First of all, according to what we learned in class*," this already represents an attempt to reflect the expert view. Later he says, *"I would say if you asked me in a test, I would say this*", again, this indicates an attempt to conform with the authority, and suppress the more concrete, intuitive thinking. Indeed, tests were used in the course, although rarely (once a year), which perhaps interfered with cultivating epistemological pluralism. Nevertheless, the questions we used were different from the original course in which we used a similar scenario of an expanding gas, but instead of asking students to predict the outcome of the process, we asked the students to explain what happens to the entropy of the system, and to describe "the law of nature that governs the process". These questions constrain students to reason using formal concepts of entropy and the 2nd law of thermodynamics, and not using other concrete but legitimate reasoning resources.

V. SUPPORTING STUDENTS IN THEORETICAL MODELING: FROM SCAFFOLDING TO WEBBING

The soft matter curriculum focuses on fundamental physics theory (such as the concept of entropy) and modeling practices that are to be used in research projects. The projects in the original course entailed an experimental investigation of the behavior of a soft matter system. The investigations were summarized in a written paper that included a theoretical model for explaining the experimental results. Explaining the behavior of complex, soft matter systems can rely on either analytical or computational models. In the original course, we introduced only analytical models of the behavior of soft materials and did not expect students to produce computational models.

In the new course, the main component of student projects was the construction and investigation of computational models. The calculations produced by the computational model are compared to experimental results. This marks a significant difference in the *learning goals* and the expected student performance between the original course and redesigned course. The construction of computational models was required to gain accreditation as a computational science course, leaving little leeway in shaping these learning goals. However, the new expected performance—constructing computational models, mandated a redesign of the *instructional supports*. Therefore, we will focus in this section on supporting students in constructing theoretical explanations for their project papers.

A. Support in the original course—Flow charts of the modeling process

The support designed in the original course was intended to help students to produce explanations of the experiments they conducted in their projects. Students were supposed to reconstruct explanations from the literature, not to build explanations *de novo* [51]. The term *reconstruction* implies that students have to recreate in their own words a theoretical model represented elsewhere (e.g., lecture slides or a scientific paper). Reconstructing a theoretical explanation is an authentic activity that resembles the practice of scientists when testing models vis-à-vis experimental observations or when reviewing the work of other scientists [52].

Our assumption was that the reconstruction of theoretical models of soft matter is in students' zone of proximal development—they cannot do it independently at their educational stage and therefore need scaffolding. The main scaffold that we used in the original course was a flow chart that represents the modeling process for soft matter phenomena that students investigated in their projects [4].

Content analysis yielded a representation of the theoretical modeling of soft matter systems in the form of a flow chart, similar to the one in Fig. 4. It starts with an experimental observation of a quantitative relationship between two measurable quantities in the system (top, left rubric). It continues with the identification of the coarse-grained degrees of freedom, which are the macroscopic parameters that vary as the system approaches equilibrium (top right). Then, the modeler chooses a simplified model of the system that takes into account the geometry and interactions of the particles or the interfaces. The model enables the quantification of the interactions among the particles that comprise the internal energy and the entropy of the system. The internal energy and entropy are then combined to yield a free energy expression. The free energy is then minimized with respect to the relevant degree(s) of freedom to yield an equation of state that explains the experimentally observed quantitative relationship.

The flow-chart in Fig. 4 illustrates visually the generic process of modeling used by experts and specifically its iterative aspect. Research has shown that concept maps or flow charts can scaffold cognitive processing because they can reduce cognitive load [53], enhance representation of relationships among complex constructs and provide props for communicating shared knowledge [54].

The flow chart was used in several contexts in the original course: The first was during the derivation of theoretical explanations for soft matter systems in the lesson stage of the course prior to the projects [55]. Then, flow charts were used as anchors for describing the modeling sequence in a written narrative: the students read an adapted scientific paper and were asked to describe the modeling process it entailed and to relate it to the generic modeling sequence [56]. Finally, scaffolding was provided in a handout with guiding questions for structuring the theoretical modeling process in the final papers.

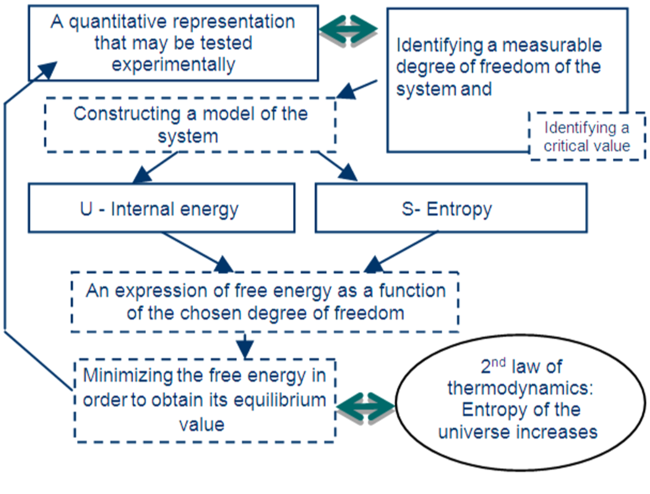


FIG. 4. A flow chart representing the modeling process—a scaffold in the original soft matter course.

In addition to the preplanned scaffolds, the instructor provided person-to-person guidance and monitoring of the derivation of the theoretical models with each student pair, in meetings or via email.

B. Support in the new course—Extending and modifying computational models

The new course based the theoretical explanations of soft matter phenomena in the final projects on computational models. In order to prepare students for explaining phenomena in their projects, we designed activities in which they constructed, analyzed and modified several fundamental computational models. The computational models were built using the VPython package [57] designed for the Python programming language. Table I summarizes the core computational models that were introduced in the course and extended in the projects:

Entropy and the 2nd law of thermodynamics were introduced between the 1st model (gas) and the 2nd model (the two-state system). Models 2–4 used the Boltzmann factor, $p = e^{-\Delta E/T}$ to determine the probability of acceptance of moves that *increase* the energy of the system (when the energy decreases, the move is always accepted; see Ref. [7] p. 231–236 or Ref. [59] p. 581). We derived the Boltzmann factor using the Boltzmann definition of entropy, and under the assumption that the temperature of the surrounding environment remains constant when small amounts of energy are transferred to or from it (see Ref. [46], p. 485).

A typical lesson or a sequence of lessons start by outlining a system or phenomenon to model (e.g., the phase separation of a binary mixture at a certain temperature) then discussing the critical features of the system that should be represented in the model. Then, for an hour or more, students in groups of two or three engage in constructing, modifying, or analyzing a "skeletal code" of one of the core models. At the end of the lesson, the groups share their models with the whole class and discuss their results. These lesson formats were inspired by the idea of webbing [36], since running the skeletal code, then modifying or adding features to it, provides a learning object that students can extend and adjust on their own thereby develop their understanding of the model. For example, when modeling a binary mixture of two interacting fluids that phase separate, students were given a code representing a mixture using a 2D square lattice, and performs a step that changes the configuration of the system by exchanging two neighboring particles (if they are of different types). The students first ran the code, then modified the energy calculation and observed the influence of their modification on the average configuration of the system.

The programs did not include advanced computational techniques such as object-oriented programming, rather, focused on fundamental procedures such as loops, functions, and manipulation of lists or arrays. Approximately two-thirds of the course involved the guided construction of the models in Table I, and the remainder was dedicated to computational projects. The projects were usually conducted in the same working groups that were formed in the lessons. All of the computational models that students produced in the projects were based on the one of the core models [60]. Some models entailed major modifications and additions, and some required only minor changes. In other words, the core models from the initial part of the course, served as the supportive "webbing" for the building the computational models in the project part of the course.

But providing students with a webbing core model did not replace teacher guidance. All students needed consultation with the teacher after the computational model was constructed, and produced results. Weighing and scrutinizing experimental or theoretical results with colleagues (e.g., a simulation expert with a theorist in the field) or the literature is a practice of scientists, and was not intended to be performed independently by students. Additional teacher guidance was needed for building the computational models. This extent of teacher guidance depended both on the sophistication of the computational model, and on the programming background of the students. For example, a pair of students with no computational background built a model of self-assembly that

TABLE I. The fundamental computational models that were studied in the redesigned course.

Computational model	Description	Phenomena
1. A gas of random walkers	Random walk on a 2D Square or 3D cubic lattice	Diffusion of a gas
2. Two-state systems	Random walk with energy decrease when reaching a binding site	Adsorption or desorption processes, such as ligand binding
3. Binary mixture	Random exchange of two neighboring particles of different types, with nearest neighbor energy interactions	Phase transition between mixed or phase separated mixture. Phase diagrams of mixture composition and temperature
4. Surfactant self-assembly	"Slithering snake" model [58] for dimers with a hydrophobic "tail" and hydrophilic "head"	Formation of micelles and bilayers of lipids. The critical micelle concentration
5. Polymer	"Slithering snake" model [58] of a single self-avoiding chain in solution	Scaling of the size of a polymer "blob" according to the number of monomers

contained a procedure that calculates the number of surfactants in a micellar cluster. This model contained a recursive procedure that searches the number of neighboring particles in a cluster. Recursion was not used in the core models and the teacher had to build it with the students step by step. In addition, the students converted the 2D model that was used in the lessons, to a 3D model. They did this part independently, without guidance from the teacher. The description of this pair and a few others is summarized in Table II in the Appendix.

C. Support and perceptions of independence

The socioconstructivist approach that guided us in the design of the original course, led to mixed results. Almost all student projects included experimental investigations, but the level and scope of the reconstructed theoretical explanations varied significantly between projects. Only few students were able to reconstruct a model from the scientific literature on their own without extensive teacher guidance. When the derivation entailed mathematical approximations unknown to the students, the teacher had to write the entire derivation line after line with the students. The flow chart might have explicated the modeling process, but was not an appropriate scaffold for reconstructing the theoretical models in student papers.

Some exceptional students were able to derive and reconstruct theoretical models from the scientific literature. Jerry was one of those students. He reconstructed an extensive theoretical derivation, with occasional consultations with the teacher when he felt stuck. This was one of the most independent performances of writing a theoretical explanation for a soft matter phenomenon. Yet, in an interview afterwards, Jerry questioned the significance of his contribution to the final artifact because he asked the teacher for guidance [5]. Jerry's comment raised our attention to the discouraging emotional effect of needing teacher support. We conclude that for most introductory level students, reconstructing analytical models from the scientific literature is not a reasonable expectation.

Students were more independent in constructing computational models in the redesigned course. The sample of projects in Table II shows that most students were able to extend the core models and adjust them, if the extension did not require new programming concepts (e.g., recursion). It also shows that students with strong prior programming knowledge were able to extend the models with little or no guidance. Students needed consultation with the teacher but in most projects, they constructed the model on their own. Only two (out of seventeen) projects required the teacher to build the code with the students, line after line.

To corroborate this interpretation, we analyzed student responses to an open-ended survey that was administered at the end of the 2017 school year. One of the survey items asked "how does the learning method in the program differ from science learning in school?" Students mentioned several aspects such as the extensive use of computers, better teachers, the level of content and more. Leah, a 10th grader, named the following differences: *In the program, we learn independently instead of teachers "feeding us with a spoon." In addition, there is an emphasis on teamwork and the outcome is a better (learning) experience*.

Leah wrote that learning in the redesigned course is more independent than in school. She also emphasized group work and a better atmosphere than in school. Leah had prior programming knowledge, and needed relatively little support when working on her computational models. In the whole group of respondents, the most common theme, mentioned in 40% of the responses, referred to "independent or self-paced learning" as distinguishing between the learning approach in the program and the one that they are used to in school. This reflects an important feature of the redesigned course—it fosters independence. To conclude, building instructional support as an adjustable web, enables a more independent construction of models in the redesigned course.

VI. DISCUSSION

This paper presented a reflection on the design of an elective course on soft matter for capable high school students. We examined the differences in epistemology and instructional support between the original and redesigned course and asked whether it represents a shift from constructivism towards constructionism. In the discussion, we situate our case study in the general practice of curriculum design.

A. Epistemological pluralism in learning entropy

Following diSessa [27] we show that computational models provide a semiformalism for bridging the formal probabilistic thermal-physics concepts and their intuitive, concrete basis. Our case study shows that building computational models alongside mathematical models legitimates multiple forms of modeling and reasoning, some more formal than others. For example, when discussing project *B* about the adsorption of polymers (see Table II), the teacher asked: why does the amount of adsorbed material decrease when the temperature increases? Student I said "because there are more 'kicks' from the molecules of the solvent", student II added "because the probability to detach from the surface, increases according to the Boltzmann factor," and student III said "because the overall energy in the surroundings (the solvent) in larger, and therefore the energy transferred from the system (the adsorbed polymer) to the surroundings yields a smaller increase in entropy" (which does not compensate the decrease in entropy of the system). Although the answers of students II and III are more formal and grounded in theory, the concrete explanation of student I is a legitimate semiformal interpretation of the process.

In addition to encouraging a variety of legitimate theoretical explanations, the construction of computational models is less restricted to a specific method than mathematical modeling. This is also reflected in some of the students' responses to the questionnaire item: "how do the learning methods in the program differ from science learning in school?" For example, Daisy—a 12th grade student wrote that

> *… the use of computers is also not constrained as it is in computer science courses in school. We learn the computational tools, but we are encouraged to think of many ways to use them when programming each problem.*

Encouraging students to think of several ways to construct models, and not presenting one dominant modeling process, marks a significant shift in the new design of the soft matter course. While in the original course we expected students to refine the concrete, intuitive ideas (such as the "natural tendency towards disorder"), in the redesigned course, students move back and forth between the dynamic, visual computational models, their underlying code, and the formal statistical, thermal physics methods.

Nevertheless, including computational modeling is not an educational "panacea" that fixes all of the difficulties of learning thermal physics. This is illustrated by student S8 who made the classic mistake when he treated the snapshots in Fig. 3 as macrostates despite his extended interaction with random walk simulations. S8 also mentioned tests and class discussions that seem to "tune" his reasoning towards the formal approach, which he considered more authoritative. The course indeed included one written exam, and although we embraced epistemological pluralism in student projects, preparing for exams might have directed them towards a more "constructivist" epistemology.

B. Instructional support and independence

Constructing (and even reconstructing) theoretical explanations for phenomena in complex systems such as soft matter systems is a challenging task for introductory level students. In the original soft matter course, we used flow charts as scaffolds intended to help students to identify the typical structure of these explanations, but this scaffold did not substitute the need for teacher support. In the redesign we employed the webbing approach, by centering instruction on core computational models that students can extend and modify for theoretical explanations in their projects. The webbing approach did not wean the need for teacher support, but reduced it considerably when compared to the original course.

Student-directed discovery learning is associated with increased interest in, and motivation to do, science [61]. One source of motivation is the engagement in practices that resemble the practices of an adult or expert. Students in the courses we discussed in this paper do both—they engage in building or reconstructing models like experts, and they do so independently to a certain extent. Fostering independence is another important factor to consider in project-based courses.

Constructionism is a theory that emphasizes student-directed discovery learning and embraces more playfulness and creativity than constructivist learning methods such as inquiry learning [62]. This also characterizes the difference between scaffolding and webbing. While scaffolds are static entities that do not promote creativity, webbing invites students to be creative in adjusting and reshaping the basic program given to them. For example, some of the students in the computational soft matter course invested considerable effort in picking colors and shapes when building their computational models. Constructionism embraces these creative initiatives since they may open a serendipitous path to learning. The redesigned course indeed fostered more independence and creativity than the original course. However, due to constraints of time and limited programming knowledge, we cannot rely on webbing to provide support and teacher's guidance is still crucial, especially if the core codes require intricate adjustments.

C. Blending constructivism and constructionism

We have shown in this study some evidence for the positive consequences of curriculum design decisions that are rooted in constructionism. The truth is that we were not aware of the ideas of epistemological pluralism, or the concept of webbing when we (re)designed the soft matter course. We knew, of course, about Papert's work and constructionism, we read about integration of computation and consulted researchers that used programming in their physics curricula. But we did not design the curriculum according to constructionist principles. In a way, the model of educational reconstruction [8] that guided us reflects a curriculum design model of bricoleurs: suggesting activities, examining instruction via empirical research, and changing it if needed. A constructionist curriculum is an ever-changing instructional object. By constructing it, the designer's own understanding of the topic evolves, and the new ideas are then put back into the reconstructed design.

While the redesigned soft matter curriculum reflects a shift towards constructionism, we have not abandoned constructivism. The original course and the redesigned one were both built according to a coherent storyline in which new ideas are added to students' prior knowledge. In the new course, we applied constructivist principles to the design of the coding: they are related to and extend prior programming principles. We also expected the students to justify the construction of computational models based on a formal set of rules, rooted in statistical physics. Thus, the redesigned course reflects a partial shift towards constructionism. In several respects, such as the sequence of lessons in which students discover the meaning of entropy—it is still a constructivist endeavor. We believe that a physics curriculum must follow constructivist principles in building the progression of ideas, constructionism does not provide clear guidelines for this effort. Constructionism contributes the approach for designing learning environments and activities that foster student agency and embracing epistemological pluralism by providing legitimacy to semiformal student reasoning.

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APPENDIX

Student projects in the redesigned course were extensions of the fundamental models that were studied during the lessons. Sometimes, a project entailed a combination of

TABLE II. Sample student projects from the redesigned course with descriptions of the core models, their extensions, and teacher guidance.

Project description	Fundamental models at the core	Extensions of the core model	Student background and teacher guidance
A. Modeling the effect of concentration on the size of micellar clusters in a solution of sodium dodecyl sulfate	Surfactant self-assembly (model 4)	1. Converting the 2D model into a 3D model 2. Calculating the size of a cluster of surfactant molecules, and the average cluster size	No programming background, teacher introduced the concept of recursion and built the function with the students, but was not involved in converting the model from 2D to 3D
B. Modeling the adsorption of a water soluble polymer onto a surface	Two-state system (model 2) and polymer (model 5)	1. Creation of many chains with no overlap 2. Merging model 2 and model 5 into one code that represents the motion of polymers and their interaction with the surface	Some programming background. The students built most of the program on their own, but asked for help when analyzing the results
C. Controlled release of a liquid (drug) from a hydrogel	Random walk gas (model 1)	1. Percolation model to represent the hydrogel, through which the “drug” diffuses. Below the percolation threshold, it cannot leave the hydrogel	No programming background. The main idea for using percolation was provided by the teacher, but the programming was mostly done by the students
D. The effect of osmotic pressure of salt on the radius of vesicles in an aqueous solution	Random walk gas (model 1) two-state system (model 2)	1. Realizing pressure as the number of times the particles “hit” the membrane 2. Building the vesicle, as a sphere with a varying radius 3. Implementing the two-state system model, for the change in “elastic energy” of the sphere	One of the students had programming experience, but this pair did very little on their own. The teacher guided them through building the entire model—they were not able to do so on their own
E. The effect of the concentration of a water soluble polymer on the viscosity of the solution under gravitational pull	Polymer (model 5), two-state system (model 2)	1. Creation of many long chains with no overlap 2. Calculating the average velocity of the polymer 3. Adding a gravitational energy calculation and implementing energy driven motion	Both students had strong programming background. They built the code in an object-oriented manner, with no help from the teacher. The teacher identified a wrong assumption in the code, which they fixed

two such fundamental computational models. Table II describes five projects, the fundamental computational models that were used, the main extensions/additions that were implemented by the students, the programming level of the students and the main aspects of guidance provided by the teacher.

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[48] In addition, since the learners were 10th graders and this was their first introduction to physics, we had to introduce Newton's 2nd law and Hooke's laws rigorously. A shortened version of this introduction for students who learned introductory Newtonian mechanics beforehand, would last approximately 12 meetings.

[49] This assumption is valid since the diffusion front progresses much more slowly than the particle motions. Thus, the front is quasistatic. For any position of the front, one can count the particle configurations. One then sees that as the front progresses, it is equivalent to thinking of a static system with a box size that is increasing. Increasing the box size decreases the particle density which increases the entropy. Note that it is the density that is important and not the extensive quantities such as the volume of the container or number of particles.

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[55] In the lesson phase of the program the flow chart was used as reflective device. In the first lessons, the modeling process soft matter systems was derived by the teacher and then summarized using a PP slide with a flow chart, similar to the one in Fig. 4. In subsequent lessons, students were asked to summarize the modeling process in worksheets with a flow chart of empty rubrics (boxes). Students were asked to fill the rubrics in the flow chart and their responses were then compared with the expected structure of the flow chart in a class discussion.

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